Pion electromagnetic form factor and Fock state components

J. P. B. C. de Melo*, T. Frederico†, E. Pace** and G. Salmè‡

*CCET, U. de Cruzeiro do Sul, 08060-070, and IFT, U. Est. Paulista 01405-900, São Paulo, Brazil
†ITA-CTA, 12.228-900 São José dos Campos, São Paulo, Brazil
**U. di Roma "Tor Vergata" and INFN, Sez. Tor Vergata, Via della Ricerca Scientifica 1, I-00133 Roma, Italy
‡INFN, Sez. Roma, P.le A. Moro 2, I-00185 Roma, Italy

Abstract. The pion electromagnetic form factor in the space- and time-like regions are for the first time analyzed within a light-front model, that allows one to address the fundamental issue of non-valence components of the pion and photon wave functions. Our relativistic approach is based on a microscopic vector meson dominance model for the dressed quark-photon vertex, and on a simple parametrization for the emission /absorption of a pion by a quark. The comparison with the experimental data shows a high quality agreement in the whole kinematical region explored.

Keywords: Relativistic quark model, Vector-meson dominance, Electromagnetic form factors, pion
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In this contribution, some highlights on i) physical motivations, ii) ingredients and iii) comparison with the data of our approach for investigating the pion electromagnetic (em) form factor are presented. All the details can be found in our recent papers [1].

The choice of investigating the pion em form factor, in the whole kinematical region explored by a virtual photon, is dictated by the possibility to go beyond a simple description in terms of the valence component of the pion state. In order to accomplish this, we need a meaningful Fock expansion of the pion state, like the one obtained within the light-front (LF) dynamics [2].

The covariant expression [3] for matrix elements of the em current of hadrons, devised by Mandelstam [3], represents the starting point of our analysis. In the time-like (TL) region it reads

$$j^{\mu} = -\imath e \int \frac{d^4k}{(2\pi)^4} Tr \left[S_Q(k-P_h)\lambda_{\overline{h}}(k-P_h, P_{\overline{h}}) S(k-q)\, \Gamma^{\mu}(k,q)\, S(k) \overline{\lambda}_h(k,P_h) \right] \quad (1)$$

where $S(p) = 1/(\not{p} - m + \imath\epsilon)$ is the constituent quark propagator struck by the photon, $S_Q(p)$ the propagator of the spectator constituent quark (for a meson) or diquark (in a simple picture of baryons), $\Gamma^{\mu}(k,q)$ the quark-photon vertex, q^{μ} the virtual photon momentum, $\lambda_h(k,P_h)$ the Bethe-Salpeter amplitude of the hadron; P^{μ}_h and $P^{\mu}_{\overline{h}}$ are the hadron momenta. In the space-like (SL) region $P^{\mu}_h \to -P^{\mu}_h$, $\overline{h} \to h'$ and the initial hadron vertex is $\lambda_h(-k,P_h)$. Unfortunately, a fully field-theoretical description of the quark-photon and quark-hadron vertexes is still far from being a realistic one. Therefore we have to introduce some approximations, based on physical motivations or convenience (to speed up the calculations), to be checked a posteriori through a very detailed comparison with the existing data (we adopt linear plots for comparing our results with the data, and not only the widely adopted log-plot). The chain of approximations begins with an integration over the LF variable k^- in Eq. (1), retaining only the contributions from the poles of fermionic propagators. Within a LF approach, one can decompose the fermionic propagator in two contributions: i) an on-shell term that has a pole in the LF variable k^- and ii) an instantaneous term, with a characteristic *independence* upon the LF variable k^-. Following the previous approximation and introducing the mentioned decomposition, the matrix element in Eq. (1) has contributions with no instantaneous terms and contributions with at least one instantaneous term. Our second approximation is represented by the application of a vector meson dominance (VMD) model for the quark-photon vertex. In our approach the VMD is implemented at the level of vertexes [1], namely the plus component of $\Gamma^\mu(k,q)$ is given by

$$\Gamma^+(k,q) = \sqrt{2}\sum_{n,\lambda}\left[\varepsilon_\lambda \cdot \widehat{V}_n(k,k-P_n)\right]\,\Lambda_n(k,P_n)\frac{[\varepsilon_\lambda^+]^* f_{Vn}}{(q^2 - M_n^2 + \imath M_n\tilde{\Gamma}_n(q^2))} \tag{2}$$

where f_{Vn} is the decay constant of the n-th vector meson into a virtual photon, *a calculated quantity in our model*, M_n (ε_λ) is the mass (the polarization) of the VM, $\tilde{\Gamma}_n(q^2) = \Gamma_n q^2/M_n^2$ (for $q^2 > 0$) the corresponding total decay width, $\left[\varepsilon_\lambda \cdot \widehat{V}_n(k,k-P_n)\right]\,\Lambda_n(k,q)$ is VM vertex function, with $\widehat{V}_n^\mu(k,k-q) = \gamma^\mu - (k_{on}^\mu - (q-k)_{on}^\mu)/(M_0(k^+,\mathbf{k}_\perp;q^+,\mathbf{q}_\perp) + 2m)$ the Dirac structure that generates the proper Melosh rotations for $^3S_1$ states, and $\Lambda_n(k,q)$ the momentum-dependent part of the Bethe-Salpeter amplitude. The next approximation will be applied to the quark-pion and quark-VM vertexes entering the on k^--shell contribution to Eq. (1) and the instantaneous one. In particular, for the meson vertex evaluated on the k^--shell, the proportionality to the 3D LF wave function for mesons has been adopted, using the meson wave functions obtained in [4], while for the meson vertexes evaluated in the kinematical region relevant for the instantaneous contribution a one-gluon approximation has been adopted, see [1]. Such an approximation results in a different (from the one used in the k^--shell contribution) proportionality between the meson vertex and the 3D meson wave function. Given the overall normalization, obtained through the charge normalization, our calculations depend only upon the ratio of the constant of proportionality for the pion (c_π) and the one for the vector mesons (c_{VM}). It is worth noting that only one constant has been assumed for all the vector mesons considered in our calculations (up to 20 vector mesons).

The hypothesys of a vanishing pion mass greatly simplifies our calculations. A model for the probability of the valence component, essential for the VMD contribution, has been developed [1]. For the emission/absorption of a pion by a quark we followed [5].

In Figs. 1 and 2, our theoretical model is compared with the experimental data, in the range $-10\ (GeV/c)^2 < q^2 < 10\ (GeV/c)^2$. In our calculations the only adjusted parameters are the constant $w_{VM} = c_{VM}/c_\pi$ and the hadronic widths for the decays of the VM with mass $> 2.1\ GeV$. All these widths have been chosen equal to $0.15\ GeV$, i.e. of the same order of magnitude of the widths of the VM's with mass $\leq 2.1\ GeV$.

The very nice results, shown in Figs. 1 and 2, encourage to apply our model to the em form factors of the nucleon, in the space- and time-like regions.

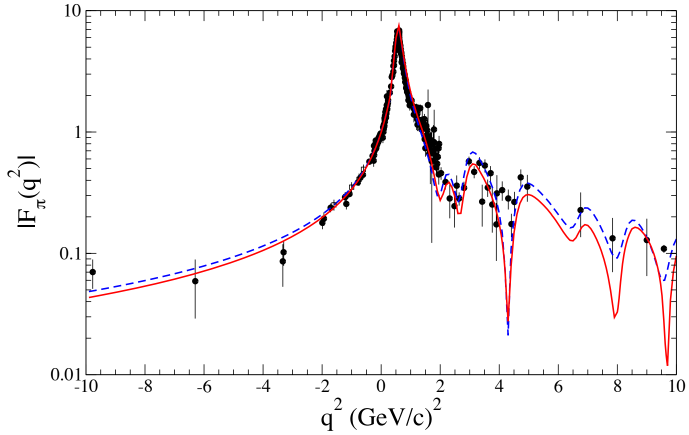

FIGURE 1. Space- and time-like form factor of the pion vs q^2. Experimental data from Ref. [6]. Solid line: calculation with the pion wave function from the model of Ref. [4], adopting $w_{VM} = -0.7$ in the instantaneous term (see text). Dashed line: the same as the solid line, but with the asymptotic pion wave function [2].

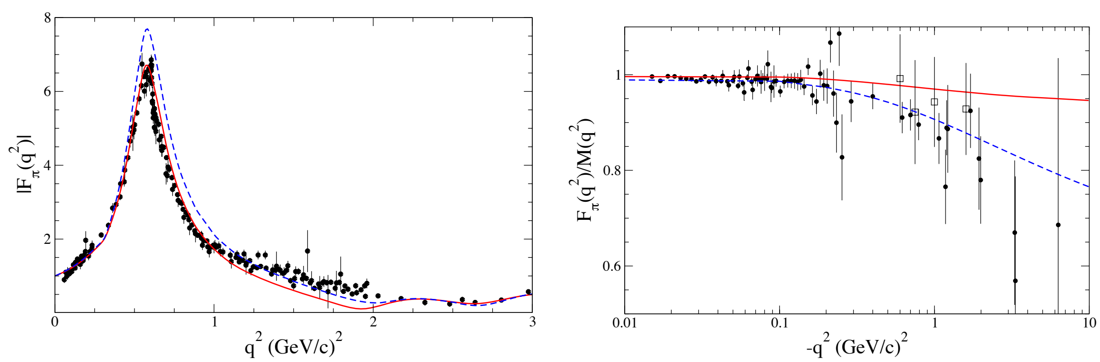

FIGURE 2. (Left) Pion form factor in the ρ-peak region. Solid line: calculation with the pion wave function from the model of Ref. [4], adopting $w_{VM} = -1.5$ in the instantaneous term (see text). Dashed line: the same as for the solid line , but with $w_{VM} = -0.7$. (Right) The ratio $R_\pi(q^2) = F_\pi(q^2)/\left[1/(1-q^2/m_\rho^2)\right]$ vs q^2, in the SL region. Full dots: data from [6]; squares: TJLAB data [7].

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